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Seismic Analysis of Morrow Point Dam

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UCRL-JC-147993

Seismic Analysis of Morrow Point Dam

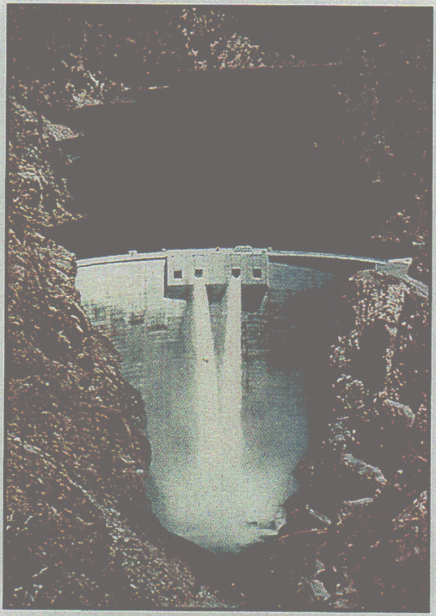
A Study for the United States Bureau of Reclamation

Charles R. Noble

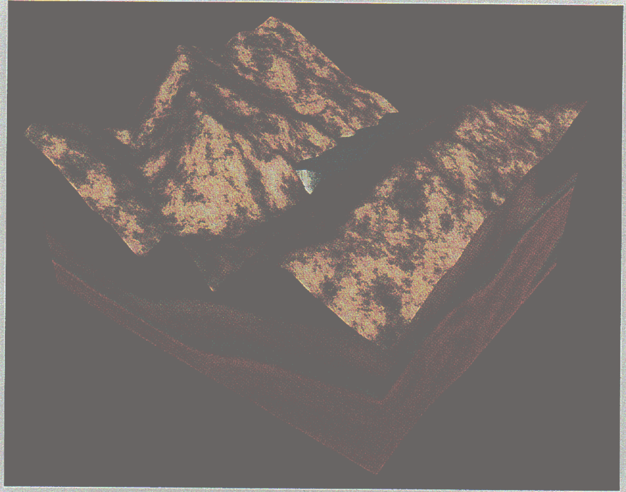
Structural and Applied Mechanics Group

New Technologies Engineering Division

April 2002



Morrow Point Dam, Colorado



Graphical Representation of Morrow Point Dam Finite Element Model

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1.0 Project Objectives

The main objective of this study is to perform nonlinear dynamic earthquake time history analyses on Morrow Point Dam, which is located 263 km southwest of Denver, Colorado. This project poses many significant technical challenges, one of which is to model the entire Morrow Point Dam/Foundation Rock/Reservoir system which includes accurate geology topography. In addition, the computational model must be initialized to represent the existing dead loads on the structure and the stress field caused by the dead loads. To achieve the correct dead load stress field due to gravity and hydrostatic load, the computer model must account for the manner in which the dams were constructed. Construction of a dam finite element model with the correct as-built geometry of the dam structure and simply "turning on" gravity in the computer model will generally lead to an incorrect initial stress field in the structure. The sequence of segmented lifts typical of dam construction has a significant impact on the static stress fields induced in the dam. In addition, the dam model must also account for the interaction between the adjacent dam segments across the dam contraction joints. As a result of these challenges, it was determined that a significant amount of code development was required in order to accurately simulate the motion of the dam structure. Modifications to the existing slide surfaces are needed to allow for appropriate modeling of the shear keys across the contraction joints. Furthermore, a model for hydrodynamic interaction was also implemented into NIKE3D and DYNA3D for fluid representation in the 3D dam system finite element model. Finally, the modeling of the 3D dam system results in a very large computational model, which makes it difficult to perform a static initialization using an implicit code. Traditionally, for these large models, the model has been initialized over a long time scale using an explicit code. However, recent advancements have made it possible to run NIKE3D in "parallel" on relatively small parallel machines as well as on the ASCI platforms.

2.0 Description of Morrow Point Dam

Morrow Point is a thin-arch, double-curvature dam located approximately 35 km (22 miles) east of Montrose on the Gunnison River in southwestern Colorado. The dam, which was constructed between 1965 and 1967, impounds approximately 144 million cubic meters (117,000 acre-ft) of water in the Morrow Point Reservoir. The reservoir extends approximately 19 km (12 miles) upstream. The dam structure is 143 m (468 ft) high with a crest length of 221 m (724 ft). The thin arch structure ranges in thickness from 3.7 m (12 ft) at the crest to 16 m (52 ft) at the base. The crest of the dam, at elevation 2183.9 m (7165 ft) carries a roadway across the width of the structure. The dam structure consists of a number of vertical blocks which are in contact across the vertically extending contraction joints in the dam. The vertical contraction joints of the dam are keyed to enhance shear transfer normal to the face of the dam. A typical contraction joint detail is shown in Figure 1. Under service load conditions of gravity and hydrostatic loading, the contraction joints are under a state of high compression.

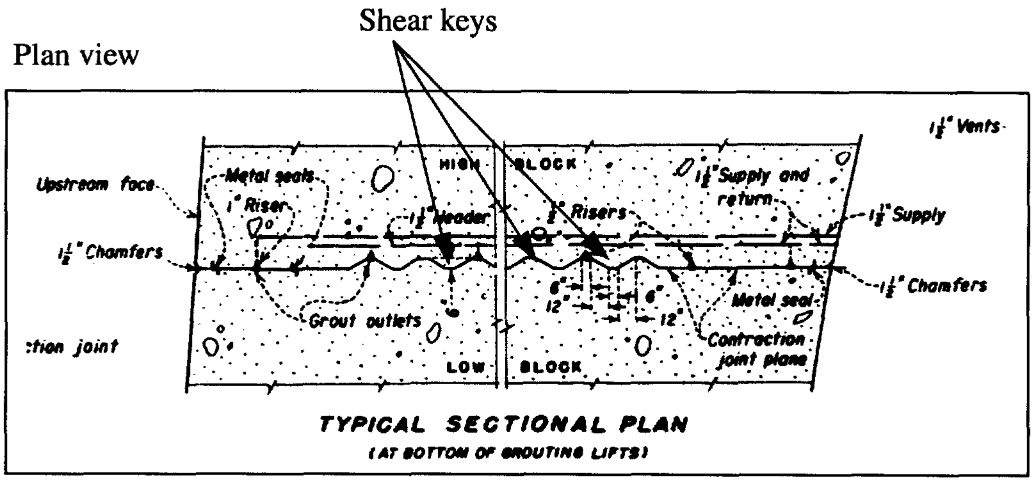


FIGURE 1. Cross-section of a vertically extending contraction joint in Morrow Point Dam.

3.0 Morrow Point Dam Finite Element Models

Four finite element models have been constructed for this study, with each model having varying degrees of sophistication. The first model consists of the concrete dam and Westergaard added mass for modeling the fluid-structure interaction. In 1933, professor H.M. Westergaard first established a rational standard procedure to take into account the hydrodynamic loadings on gravity dams during earthquakes. The concept of added mass, which he introduced for the incompressible water reservoir, greatly simplified the analysis procedure of the response of a dam considering hydrodynamic effects during earthquakes. Westergaard's assumptions were the following:

- dam was idealized as a 2-dimensional rigid monolith with vertical upstream face;
- the reservoir extends to infinity in the upstream direction;
- displacements of fluid particles are small;
- surface waves are ignored;
- only horizontal ground motion in the upstream-downstream direction is considered.

He approximated the pressure solution for an incompressible reservoir with a parabola. He observed that the "pressures are the same as if a certain body of water were forced to move back and forth with the dam while the remainder of the reservoir is left inactive". Westergaard suggested that the dynamic pressure could be expressed as:

$$p_z = \frac{7}{8}aw\sqrt{H(H-z)} = \frac{7}{8}\rho\ddot{r}_g\sqrt{H(H-z)} \qquad \text{(EQ 1)}$$

where

a = horizontal ground acceleration, in units of g

w = unit weight of water

$\ddot{r}_g$ = horizontal ground acceleration

ρ = unit mass of water

H = depth of reservoir above the base of the dam

z = distance from the base of the dam

p_z = hydrodynamic pressure at height z from the base of the dam, applied normally to the dam face.

EQ. 1 indicates that the hydrodynamic pressure exerted normally on the upstream face of the dam, is equivalent to the inertia force of a prismatic body of water of unit cross-section and length $\frac{7}{8}\sqrt{H(H-z)}$ attached firmly to the face of the dam, and moving with the dam back and forth in the direction normal to the face of the dam. This body of water is the "added mass" applied by the reservoir to the dam.

In model no. 1, the base of the dam is considered fixed in all three directions. This finite element model consists of 23,195 brick elements and 1,640 discrete elements (i.e. essentially a two force member which applies a user-specified force-displacement relationship between two specified nodes) to model the contact and connectivity across the expansion joints (see Figure 2). A requirement of the contraction joint model was that the contraction joints allow free relative motion in a vertical direction between adjacent dam segments as the gravity dead load was applied. This relative motion prevents the generation of large vertical direction shear stresses which transfer large loads to the upper abutment region of the dam - which the actual construction process of the dam prevents. For the dead load initialization, a model was constructed for the NIKE3D implicit finite element program. The contraction joints were modeled with frictionless contact surfaces for the NIKE3D initialization. This prevents friction between adjacent blocks as the dead loads are applied and does not allow inter-block vertical shears to develop. To obtain displacement compatibility in the direction normal to the dam, discrete elements were placed across each interface to transfer stresses between blocks in the normal direction. The discrete elements only allowed compression, so that tensile forces were not generated across the contraction joints if they were to open. A pictorial description of the discrete elements is shown in Figure 4.

Model no. 2 consists of the same dam model, but instead of having a fixed base it has a flexible foundation (see Figure 2). To achieve an accurate geology topography for the finite element model, a 1983 USGS topographic map was scanned and used to generate an IGES surface for the TrueGrid mesh generator. This model consists of approximately 101,000 brick elements and 1,640 discrete elements. To connect the dam model to the foundation model, a tied slide surface was used.

Model no. 3 is the same as model 2, except the water is now explicitly modeled instead of using Westergaard added mass for the fluid-structure interaction (see Figure 2). For the static initialization in the NIKE3D implicit finite element program, an elastic material was used to model the water. A low elastic modulus of 189.7 psi and a high Poisson's ratio of

0.4999 were used to achieve a low shear modulus and the bulk modulus of fresh water. For the seismic analysis, which was done using the DYNA3D explicit finite element program, the fluid material (Material 9) and an equation of state, which specified the bulk modulus, were used to model the water. A pressure cutoff and viscosity coefficient of 0.0 were assumed. A complete listing of all of the material properties used are given in Table 1 on page 4.

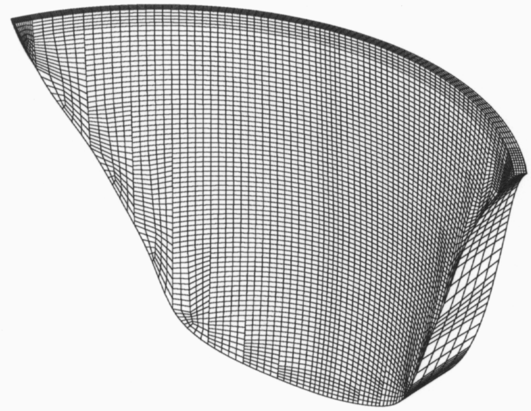
TABLE 1. Material Properties for finite element models

Material Property	*Value (lbs, in, sec)*
Elastic Modulus of Concrete	4.769E+06 psi
Poisson's Ratio of Concrete	0.15
Mass Density of Concrete	2.2500E-04 lbs-sec2/in4
Elastic Modulus of Foundation for Models 2 and 3	4.769E+06 psi
Poisson's Ratio of Foundation for Models 2,3, and 4	0.2
Elastic Modulus of Water for NIKE3D Program	189.7 psi
Poisson's Ratio of Water for NIKE3D Program	0.4999
Mass Density of Water	9.3330E-05 lbs-sec2/in4
Bulk Modulus of Water	316,100 psi
Elastic Modulus of Foundation for Model 4	3.338E+06

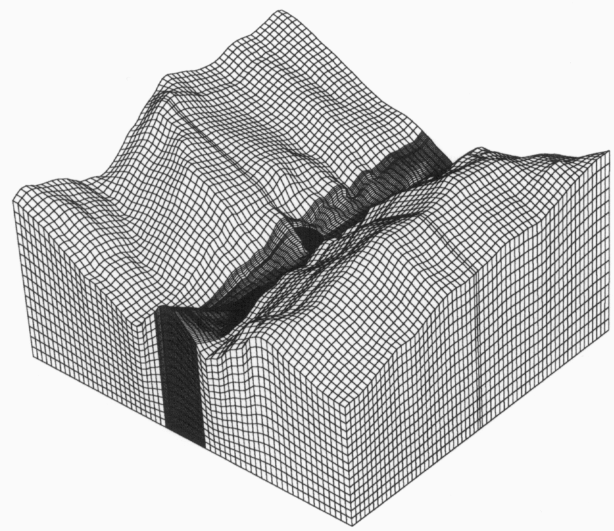
To connect the water to the foundation in this model, a tied slide surface was used. A sliding with voids slide surface, however, was used between the water and the dam. This was done so that the water could slide downwards next to the dam during the gravity initialization, preventing any unwanted stresses to be formed on the dam surface.

The final model constructed thus far consists of model no. 3 and a new feature called an abutment wedge. This wedge, or large rock, in the foundation is defined by three foliation planes - a base plane, side plane, and release plane. Figure 3 shows the finite element model with the abutment wedge modeled. A transition region was used to connect the larger elements of the foundation with the smaller elements of the abutment wedge. A tied slide surface was used between the foundation and transition region. During the static initialization in NIKE3D, a tied slide surface was used between the wedge and transition region. For the seismic analysis in DYNA3D, this slide surface was changed to a sliding with voids surface with a high coefficient of friction.

Model No. 1:
Rigid foundation with Westergaard added mass for fluid-structure interaction



Model No. 2:
Flexible foundation with Westergaard added mass for fluid-structure interaction



Model No. 3:
Flexible foundation with water explicitly modeled using linear-elastic material in NIKE3D (E = 189.7 psi, v = 0.4999) and fluid material in DYNA3D (Linear Polynomial Eqn. of State with K = 316,100 psi)

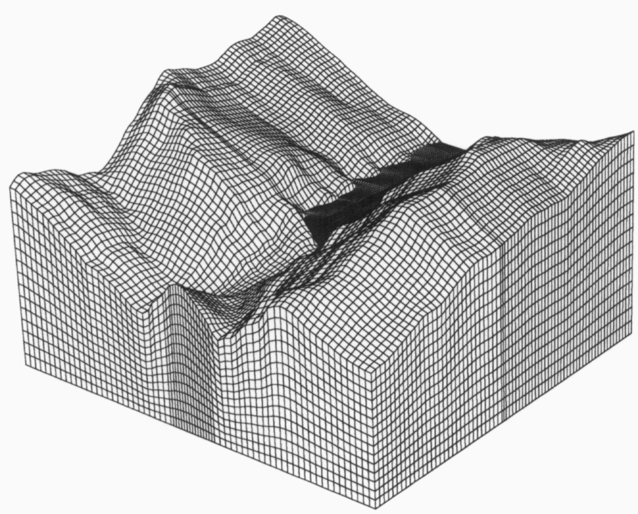


FIGURE 2. Morrow Point Dam finite element models.

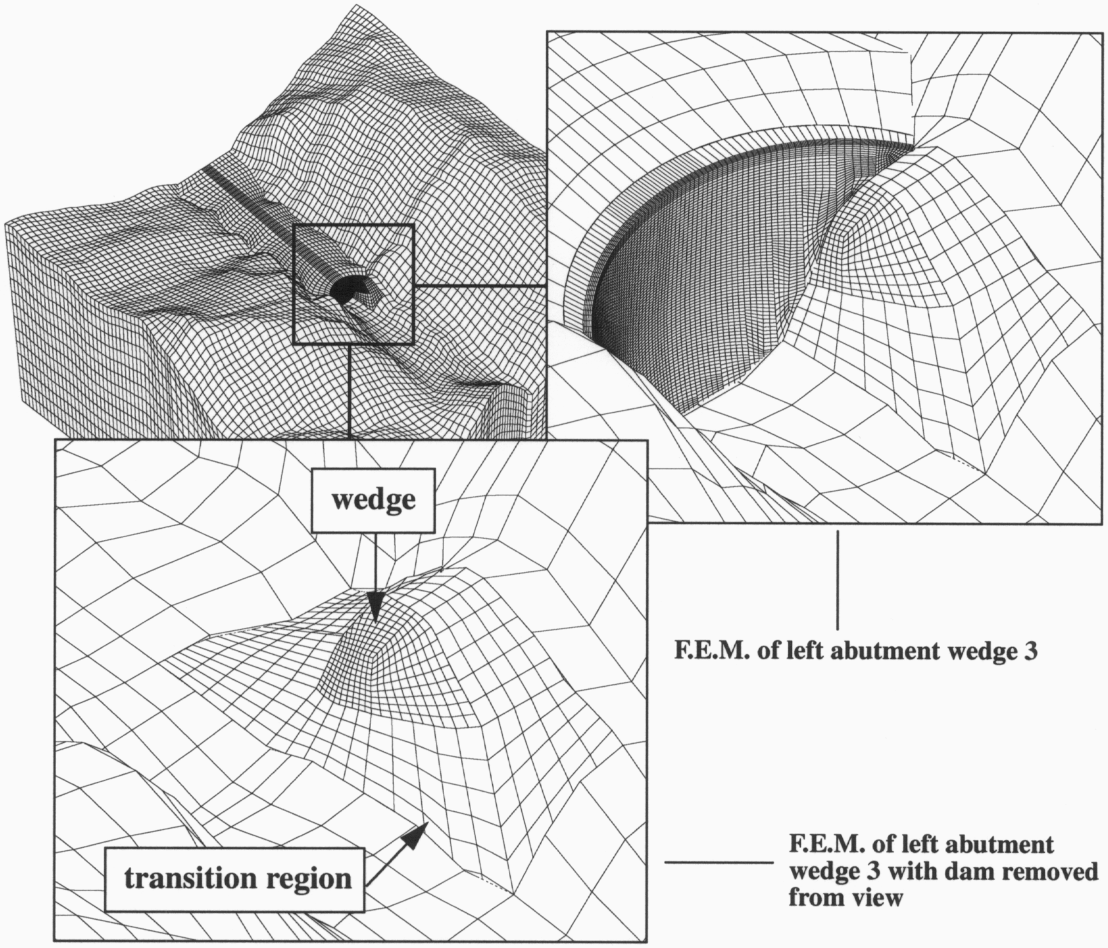


FIGURE 3. Morrow Point Dam F.E.M. with left abutment wedge 3 (model no. 4).

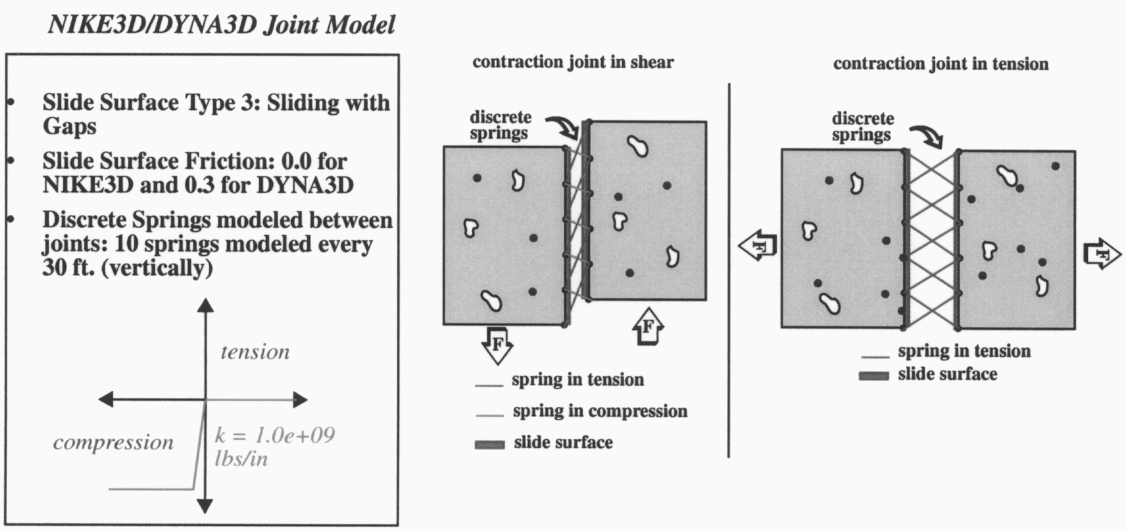


FIGURE 4. NIKE3D and DYNA3D vertical contraction joint modeling.

4.0 Finite Element Analysis Procedure

The finite element procedure for analyzing Morrow Point Dam is graphically presented in Figure 5. First, the NIKE3D and DYNA3D finite element models are generated using the TrueGrid mesh generator. Once the models are generated, a static gravity initialization is performed using the NIKE3D implicit finite element program. The bottom of the foundation has been fixed in the vertical direction for this analysis and the sides of the foundation have been given a zero displacement controlled boundary condition in the direction normal to the foundation. NIKE3D computes reaction forces for nodal degrees of freedom with prescribed displacement boundary conditions. The reason for using boundary conditions on the sides of the foundation is that the canyon would open up during the gravity initialization without them, resulting in very high unwanted stresses in the dam. Displacement boundary conditions were used instead of fixed boundary conditions, because the DYNA3D model uses nonreflecting boundary conditions on these same sides. Nonreflecting boundary conditions do not work with fixed boundary conditions, but will work if reaction forces have been placed at the same location as the nonreflecting boundary conditions. After the static initialization, the reaction forces from the zero displacement boundary conditions are gathered and imported into the DYNA3D finite element model. The seismic analyses are run using the DYNA3D explicit finite element program. The foundation has been completely fixed in all directions at the bottom of the dam. 5% mass proportional damping for the fundamental mode has been assumed for all analyses presented in this study. Once the analyses are complete, the post-processor GRIZ is used to view and analyze the results.

5.0 Eigenvalue Analysis

In an effort to validate the Westergaard added mass concept, an eigenvalue analysis was completed on the Morrow Point finite element model (see Figure 6). For an empty reservoir, the NIKE3D fundamental frequency was 4.16 hz. This compared well with Tan and Chopra's result of 4.27 hz [Ref 4]. When Westergaard added mass was used in NIKE3D (diagonal added mass), the resulting fundamental frequency was 2.76 hz. Tan and Chopra calculated a value for a full reservoir of 2.82 hz and Fenves calculated a value of 2.80 hz for a full added mass calculation and 2.5 hz for a diagonal added mass calculation. Duron and Hall [Ref 5] presented an experimental fundamental frequency of 2.95 hz for a symmetric shake and 3.3 hz for an antisymmetric shake.

6.0 Ground Motions

The ground motions used for models 1, 2, and 3 are presented in Figure 7 along with the response spectra for this ground motion. Because the base accelerations are being input 1700 ft below the dam, new deconvolved ground motions were generated by the U.S. Bureau of Reclamation and were used in model 4 (foundation model with wedge). These motions are shown in Figure 8. In essence, after propagating 1700 ft through the foundation, the base accelerations input into the dam should be approximately the same as those in Figure 7.

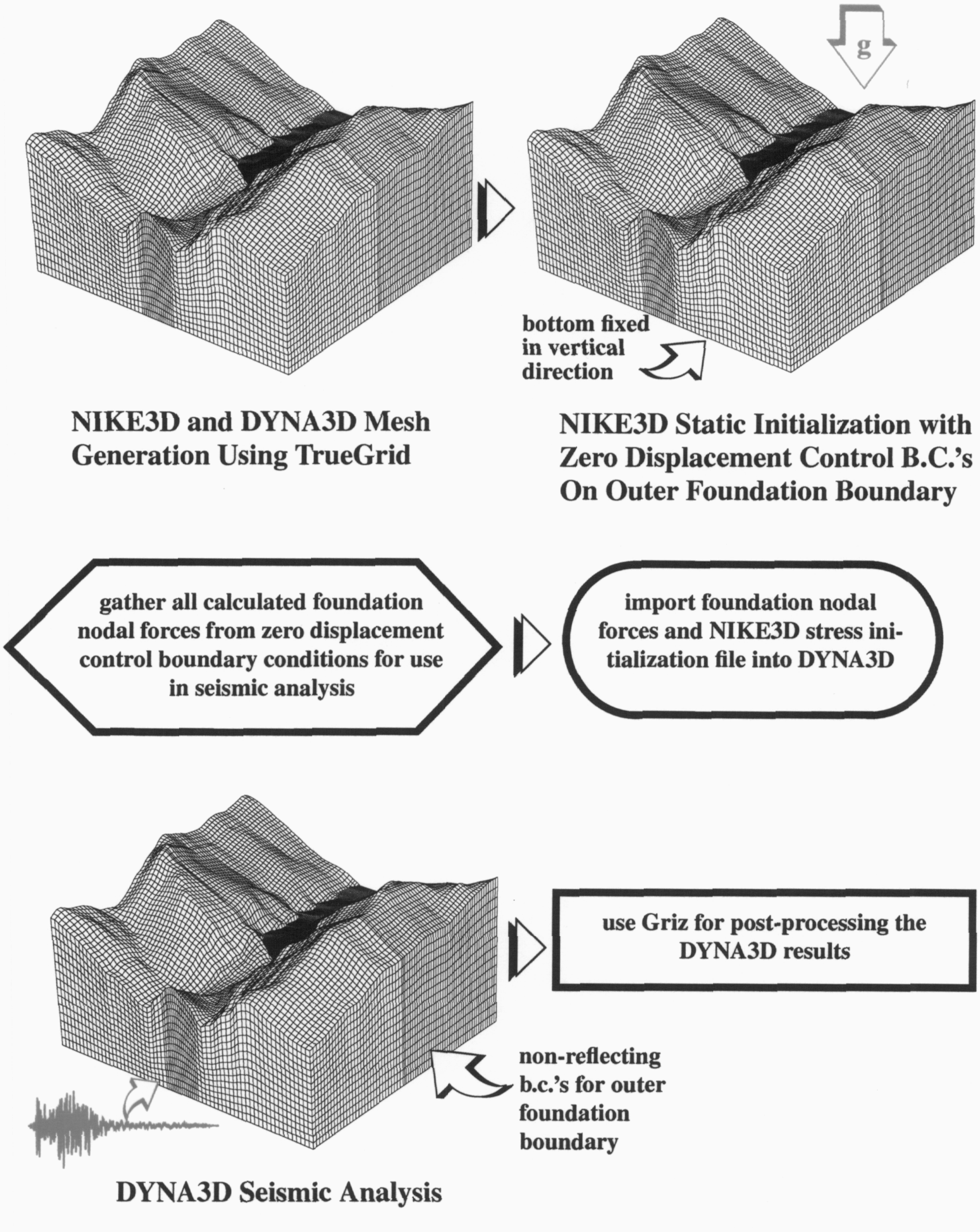
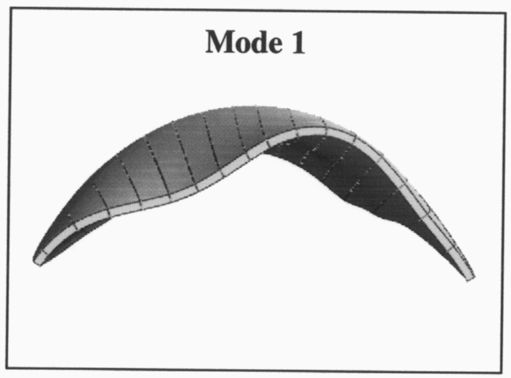


FIGURE 5. Morrow Point Dam finite element analysis procedure.

	Vibration Frequency[a] (hz)									
	Fenves et al			Tan and Chopra		Duron and Hall			NIKE3D>	
		Full Reservoir								
Mode	Empty Reservoir	Full Added Mass	Diagonal Added Mass	Empty Reservoir	Full Reservoir	Experimental	Computed with Incompressible Water	Computed with Compressible Water	Empty Reservoir	Diagonal Added Mass
1	3.23	2.80	2.5	4.27	2.82	S[b]: 2.95 A[c]: 3.3	S: 3.29 A:3.31	S: 3.05 A: 3.31	4.16	2.76
2	3.56	3.02	2.61	-	-	S: 3.95 A: 6.21	S: 5.33 A: 6.76	S: 4.21 A: 6.35	4.45	2.62
3	5.63	5.63	3.64	-	-	S: 5.4	S: 6.11	S: 5.96	6.42	4.34
4	5.96	4.82	3.98	-	-	-	-	-	7.05	5.90
5	6.43	5.78	4.38	-	-	-	-	-	8.17	5.3

a. All computed frequencies used a rigid foundation.
b. The 'S' corresponds to a symmetric shake.
c. The 'A' corresponds to an antisymmetric shake.



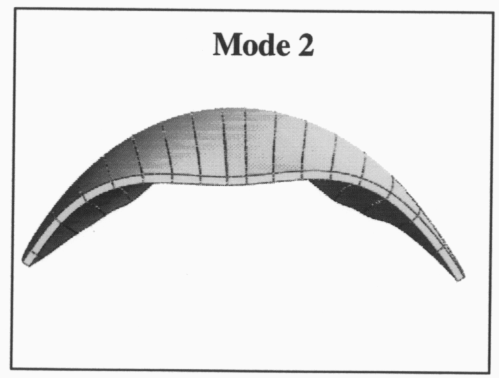


FIGURE 6. Eigenvalue analysis and literature comparison.

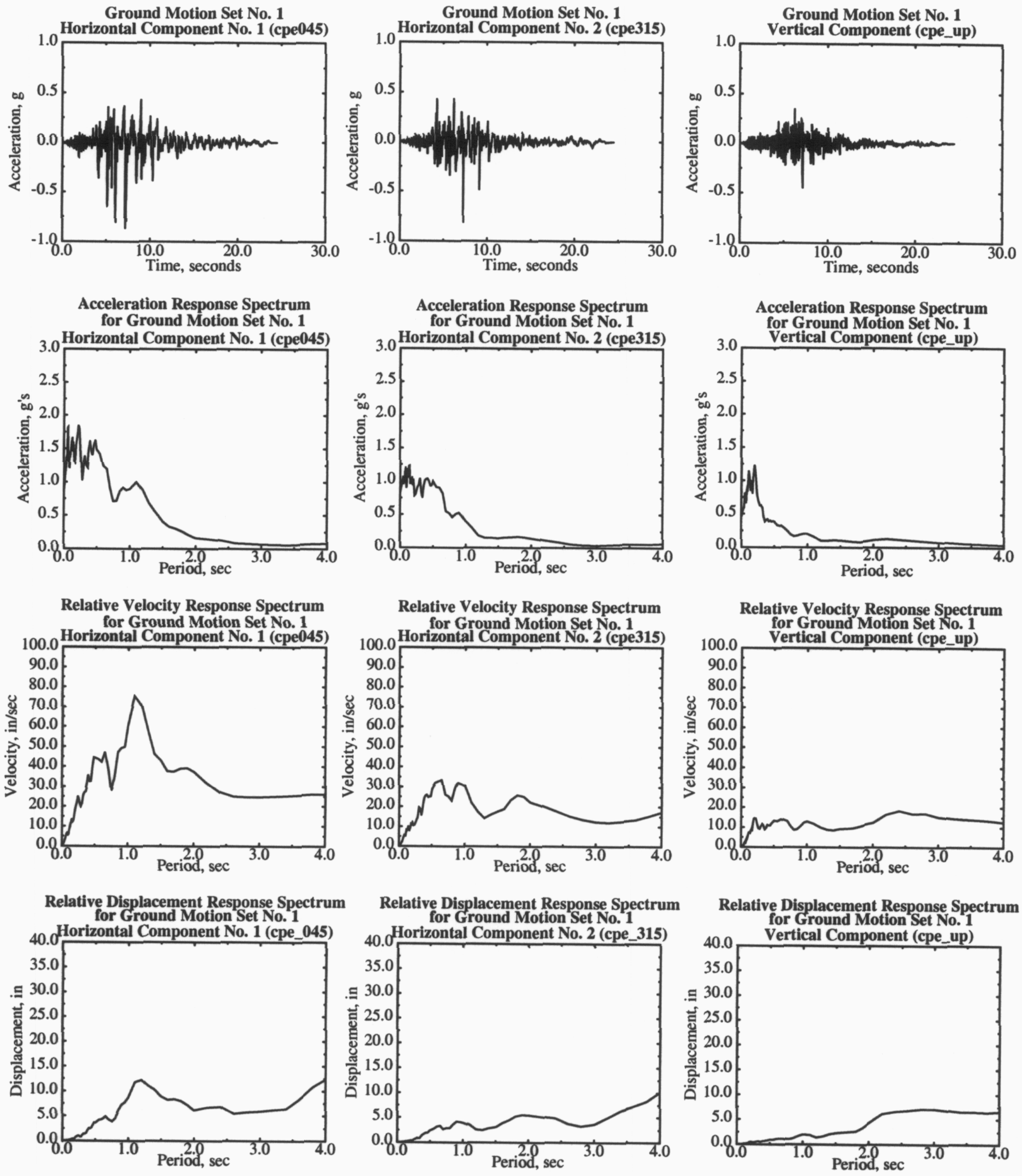


FIGURE 7. Morrow Point Dam Cerro Prieto ground motions and response spectra.

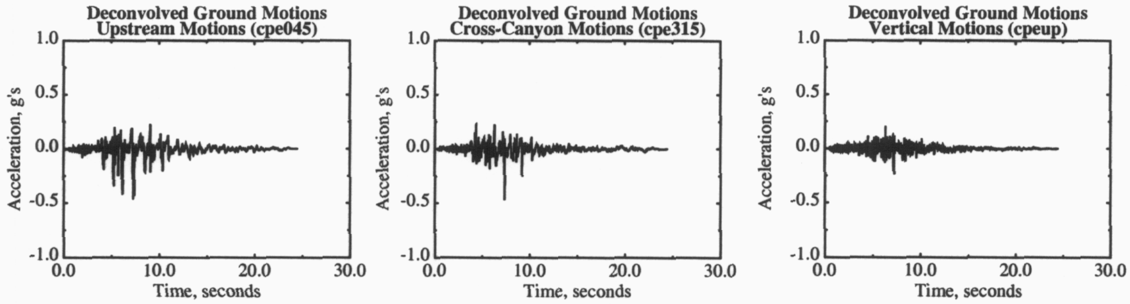


FIGURE 8. Deconvolved Cerro Prieto ground motions.

7.0 Seismic Analysis

As a precursor to the dynamic analysis, a static initialization, which included both the gravity and hydrostatic loading, was completed on all models. The hydrostatic pressure and principal stress 1 plots for all three models are shown in Figure 9. Each model, except for small deviations, resembled each other. The model which included the foundation and the water explicitly modeled had the smallest tensile stresses in the dam. Displacement time history plots of the dam (top and center) for all four models are given in Figure 10. In addition, gap opening (contraction joint separation) time history plots are presented in Figure 11. From examining the displacement time history plots the following conclusions can be made:

- Model 1 has the least amount of displacement in all three global directions. There is an increase in displacement for model 2, and model 3 has the greatest amount of displacement.
- Model 1 appears to have a higher frequency response then the other models, with models 3 and 4 having longer period motions in their response.
- By using the deconvolved ground motions, the peak response values of model 4 more resembles that of something between models 1 and 2.
- Model 3 had the largest gap openings of all of the models, with a maximum gap opening of approximately 4.5 inches at the dam quarter point. With the deconvolved ground motions, the peak values of gap openings resemble a response somewhere between that of models 1 and 2.

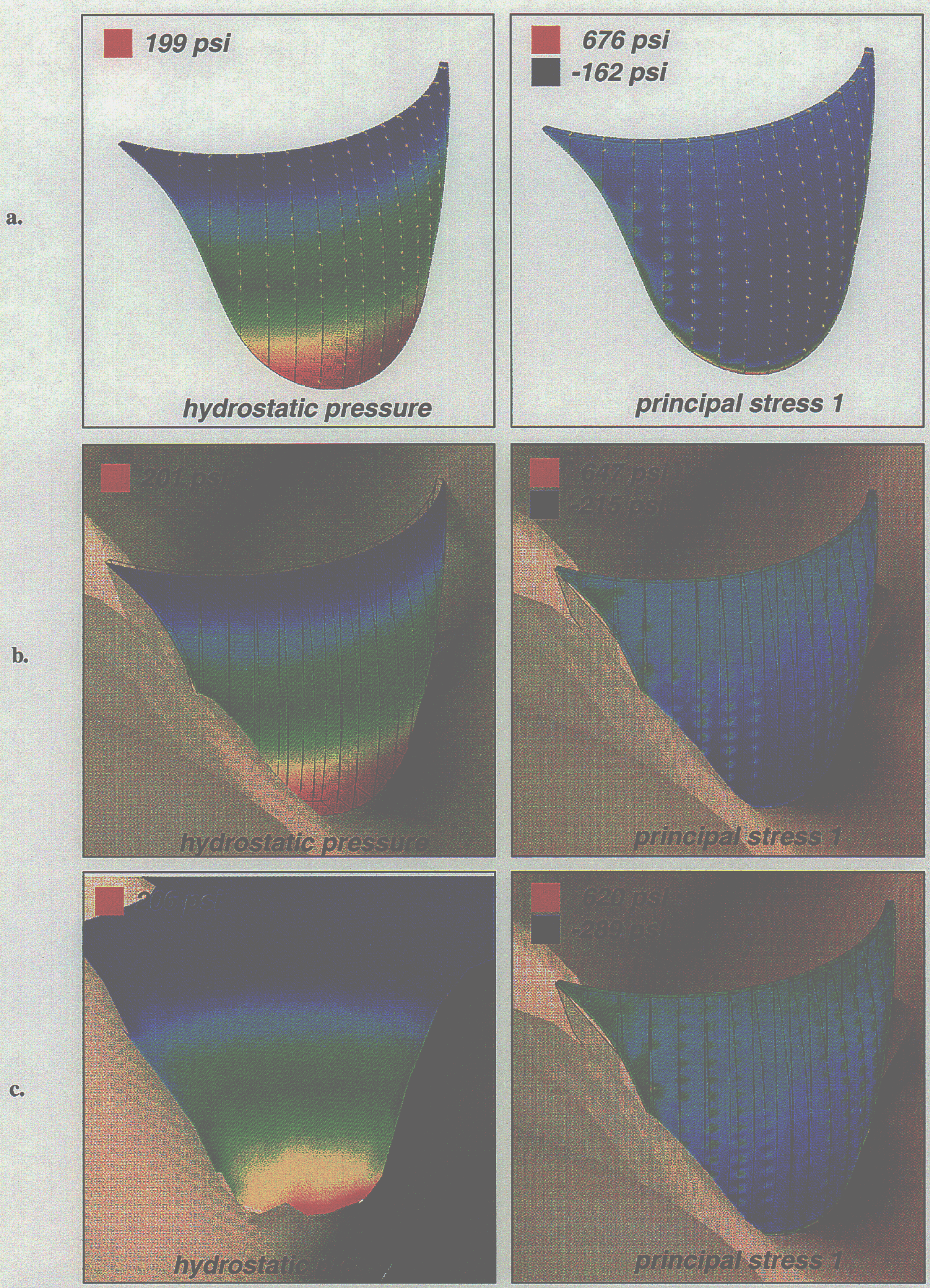
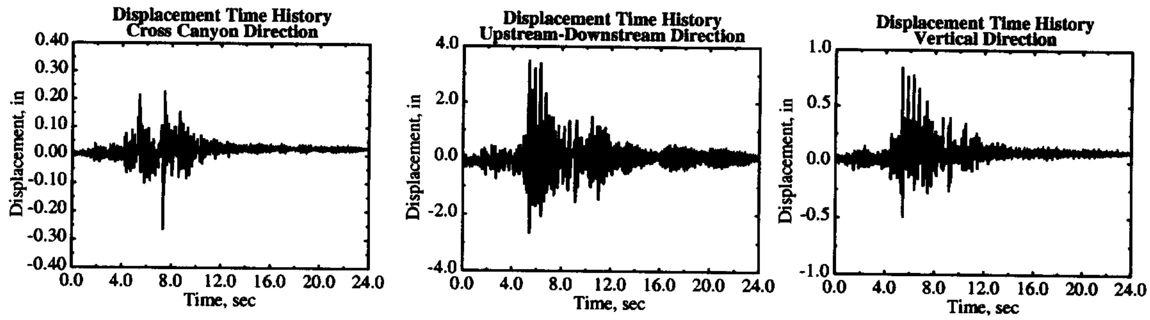
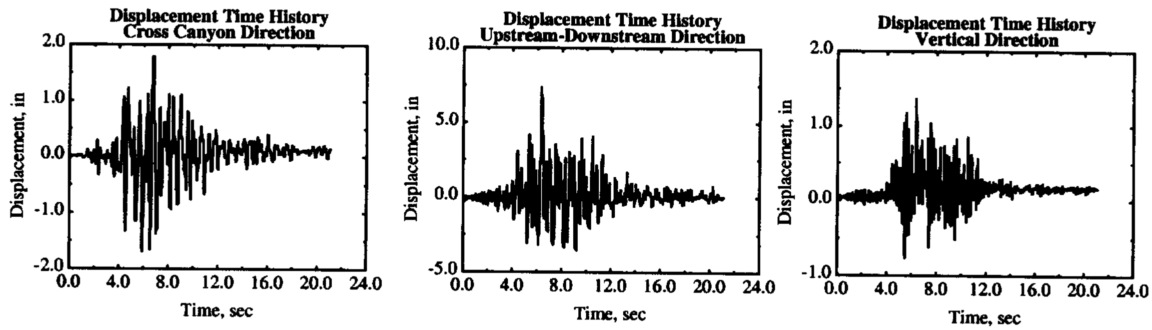


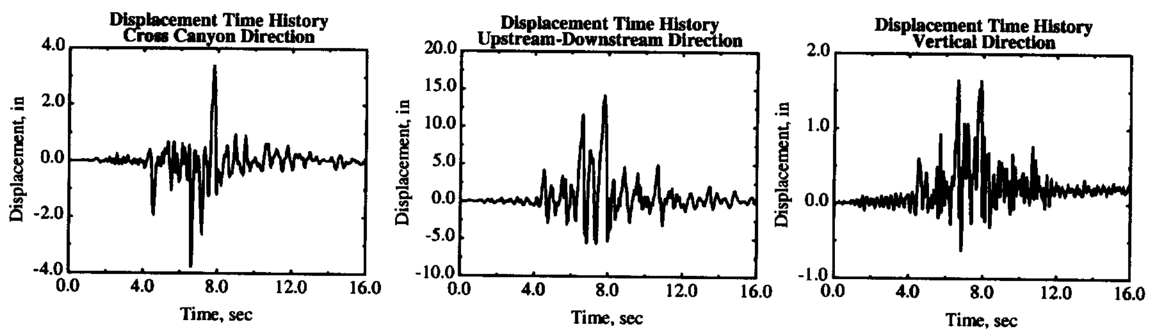
FIGURE 9. Static initialization stress plots for a). model no. 1; b). model no. 2; and c). model no. 3.



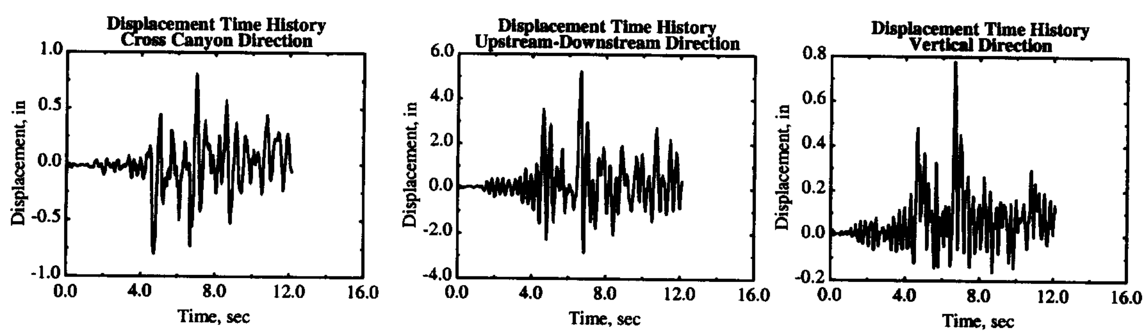
a. model no. 1



b. model no. 2



c. model no. 3



d. model no. 4

FIGURE 10. Displacement time history plots of dam (top and center) for a). model no. 1; b). model no. 2; c). model no. 3; and d). model no. 4.

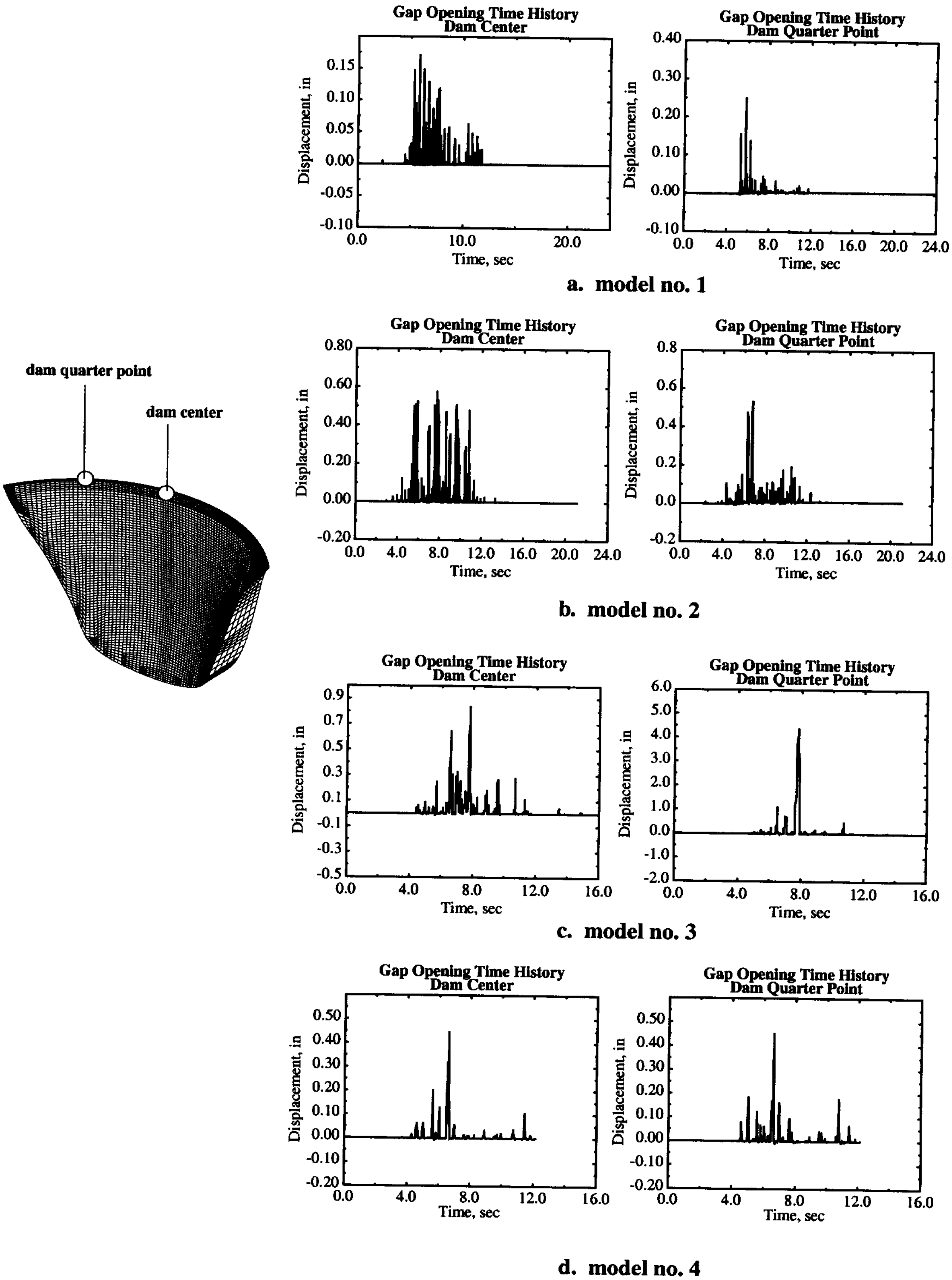


FIGURE 11. Gap opening time history plots of dam for a). model no. 1; b). model no. 2; c). model no. 3; and d). model no. 4.

8.0 Future Work

Future work will consist of the following:

1. Resolve model differences and validate that all models are indeed working correctly.
2. Hand-off contact forces between abutment wedge and dam to the U.S. Bureau of Reclamation for further study.
3. Development and implementation of a new contact algorithm, which will account for the following capabilities:

    - the ability to define separate slide surfaces along user-defined planes. This capability would allow for us to more easily model the directionality along the contraction joints. The discrete elements, in essence, would be replaced by a slide surface.
    - the ability to have separate cohesive/shear strength terms for the upstream/downstream direction and the vertical direction.
    - the ability to provide shear resistance as a function of the gap distance so that the shear keys can be properly modeled.

4. Validate the capability of being able to analyze a through thickness thermal gradient on the Morrow Point Dam.

9.0 Acknowledgements

This study was supported by the United States Bureau of Reclamation and the support and guidance of Mr. Larry Nuss is gratefully acknowledged. Dr. Mike Puso and Dr. Edward Zywicz of LLNL made modifications to NIKE3D and DYNA3D programs for this study and their timely help is greatly appreciated.

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